The Earth System Modeling Framework and Earth System Prediction Suite

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ESMF

Common Modeling Infrastructure

A series of reports and papers have outlined the need for *common modeling infrastructure* in Earth system science, for example:

- NRC 1998: Capacity of U.S. Climate Modeling to Support Climate Change Assessment Activities
- NRC 2001: Improving the Effectiveness of U.S. Climate Modeling
- Dickinson et al 2002: How Can We Advance Our Weather and Climate Models as a Community?
- NRC 2012: A National Strategy for Advancing Climate Modeling

The motivation:

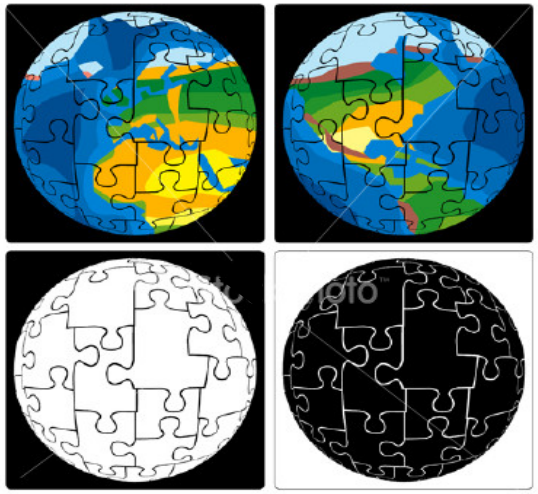
- Foster collaborative model development and knowledge transfer
- Lessen redundant code development
- Improve available infrastructure capabilities
- Support controlled experimentation
- Enable the creation of flexible ensembles for research and prediction

The Earth System Modeling Framework

The Earth System Modeling Framework (ESMF) was developed as a multi-agency response to calls for common modeling infrastructure.

ESMF delivered:

- *Standard interfaces* for model components
- High performance libraries and tools for time management, data communications, metadata and I/O, and *parallel grid remapping*



Metrics:

~5500 downloads

~3000 individuals on info mailing list

~40 platform/compilers regression tested

~6400 regression tests

http://www.earthsystemmodeling.org

Standard Interfaces

All ESMF components have the same three standard methods (these can have multiple phases):

- Initialize
- Run
- Finalize

Each standard method has the same simple interface:

```
call ESMF_GridCompRun (myComp, importState,
exportState, clock, …)

Where:
myComp points to the component
importState is a structure containing input fields
exportState is a structure containing output fields
clock contains timestepping information
```

ESMF Grid Remapping

Uniquely fast, reliable, and general – interpolation weights computed in parallel in 3D space

Supported grids:

- Logically rectangular and unstructured grids
- Global and regional grids
- 2D and 3D grids

Supported interpolation methods:

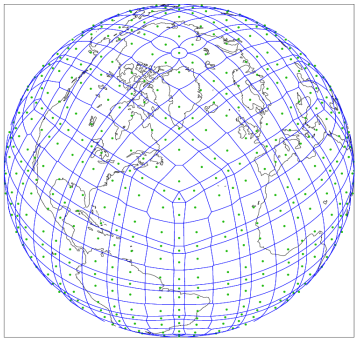
- Nearest neighbor, higher order patch recovery, bilinear and 1st order conservative methods

Options for straight or great circle lines, masking, and a variety of pole treatments

Multiple ways to call ESMF grid remapping:

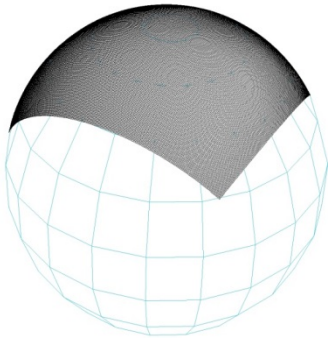
- Generate and apply weights using the **ESMF API**, within a model
- Generate and apply weights using **ESMPy**, through a Python interface
- Generate weights from grid files using **ESMF_RegridWeightGen**, a command-line utility

Some supported grids …



HOMME Cubed Sphere Grid with Pentagons
Courtesy Mark Taylor of Sandia

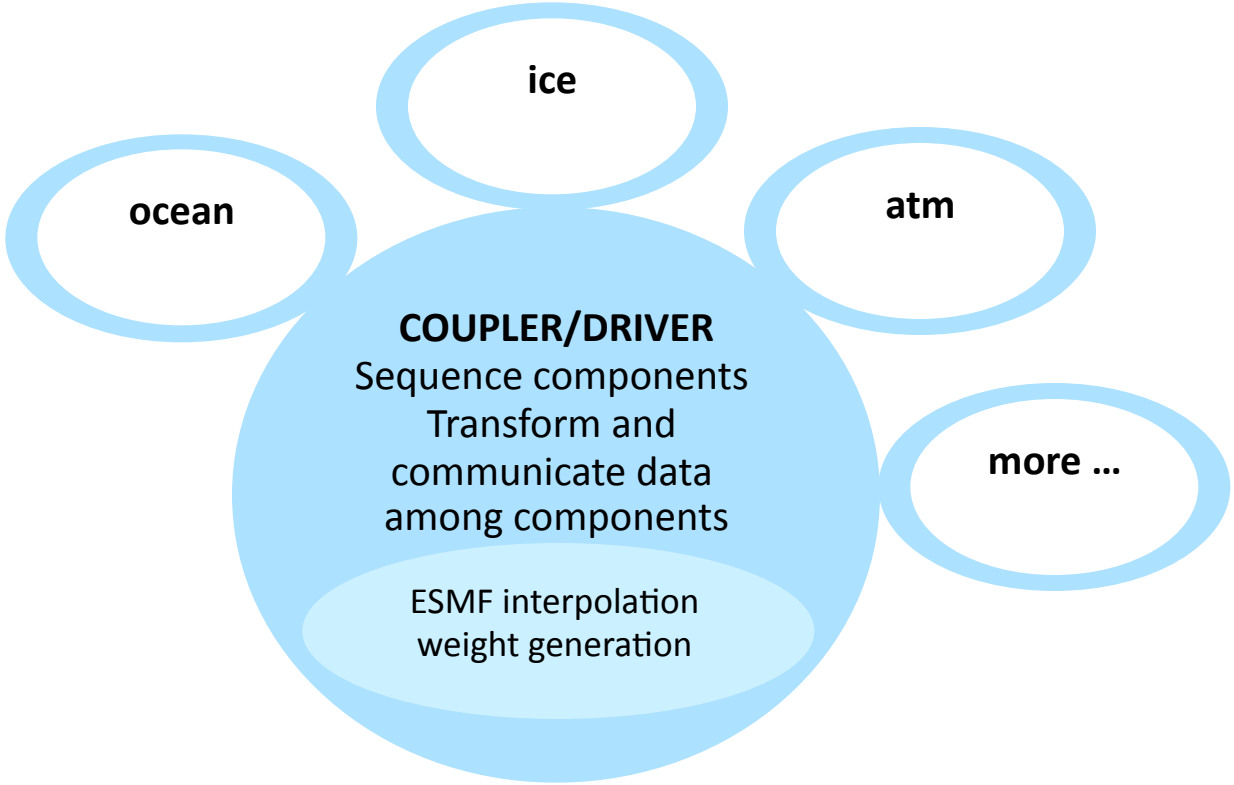
FIM Unstructured Grid



Regional Grid

Types of ESMF Use and Associated Capabilities

Modeling applications



1. Wrap components

- ESMF must represent model grids, fields, and time quantities

2. Remap grids

- ESMF generates and may apply interpolation weights

3. Construct couplers and coupled systems

- ESMF performs data communications and operations
- Time, I/O, and utility operations, and
- Component operations and interactions

Data analysis and visualization applications

ESMF interpolation weight generation

NCL, PyFerret, DOE Ultrascale Visualization Climate Data Tools (UV-CDAT), IRIS (U.K. Met Office), GrADS team, Community Surface Dynamics Modeling System …

Types of ESMF Use and Associated Capabilities

	Wrap components	Remap grids	Construct couplers and coupled systems
Grid and data representation	Yes	Yes	Yes
Time representation	Yes	No	Yes
Interpolation weight generation	No	Yes	Usually
Data communications and weight application	No	Yes	Yes
Time operations	Minimal	No	Yes
I/O and utility operations	Minimal	No	Yes
Component operations and interactions	Minimal	No	Yes

Types of ESMF Use by NOAA Center

- The NOAA Environmental Modeling System (NEMS) at EMC is where ESMF is mainly tested and run at NOAA.
- ESMF interfaces provide a way for the NOAA (and other) research centers to interact with EMC.

	Wrap components	Remap grids	Couplers and coupled system construction
NOAA ESRL	Yes (FIM for NEMS)	No	Not at ESRL
NOAA GFDL	Yes (MOM5 for NEMS, GEOS-5)	No	Not at GFDL
NOAA NCEP/EMC	Yes	Yes (NEMS)	Yes (NEMS)
NOAA PMEL	No	Yes (ESMPy in PyFerret)	Not at PMEL
NOAA SWPC	Planned (IPE for NEMS)	Yes (NEMS) – in progress	TBD

Yes

Planned or in progress

ESMF Research Inputs and Feedbacks

- The ESMF team **must innovate** to support emerging research requirements and new computational platforms in order for the framework to remain technically viable for any non-trivial use.

- ESMF works with research teams that provide cutting-edge requirements, and that test, evaluate, and provide feedback on ESMF capabilities within their applications.

- Wile GFDL and ESRL help inform ESMF design (exchange grids, fault tolerance), these active research partners are mainly outside of NOAA. They include:
  - CESM and DOE modelers (for grid remapping, coupling architecture)
  - Navy modelers (for optimization, coupling architecture)
  - NASA modelers (for data assimilation, very high resolution grids)
  - Many users of ESMF grid remapping tools (including U.K. Met Office)

- These interactions (often funded through research calls) make it possible to create ESMF infrastructure that is sufficiently flexible and powerful to efficiently couple components from NOAA research labs and other centers.

Types of ESMF Use by Some Other U.S. Centers

	Wrap components	Remap grids	Couplers and coupled system construction
CESM	Yes	Yes	In progress
Navy global and regional models (COAMPS, NavGEM-HYCOM)	Yes	Yes	Yes
NASA GEOS-5	Yes	Yes	Yes
NASA Model E	In progress	In progress	In progress
Modelers with new dycores and grids: HOMME (NCAR/Sandia), MPAS (NCAR/LANL), ORCA, hydro and surface modelers, others …	No	Yes	No
Data and viz: DOE UV-CDAT, IRIS (Met Office), NCL, GRADS team (COLA), others …	No	Yes	No

Yes
Planned or in progress

Performance

The ESMF team tests the performance of key capabilities against comparable infrastructure (usually from CESM) and prepares and posts reports with results:

http://www.earthsystemmodeling.org/metrics/performance/

Reports that include comparison to other packages were reviewed before posting for fairness and accuracy by the developers of the other package.

Example performance findings:

- ESMF component overhead is typically negligible.
- The performance of the ESMF weight application to 16K processors is about the same as the DOE implementation in CESM.

What Users Say About ESMF …

User feedbacks from NCAR CGD, NCAR MMM, COLA, the Navy, NASA, and other organizations are collected here (grid remapping or coupled system s):

https://earthsystemcog.org/projects/esmf/user_feedback

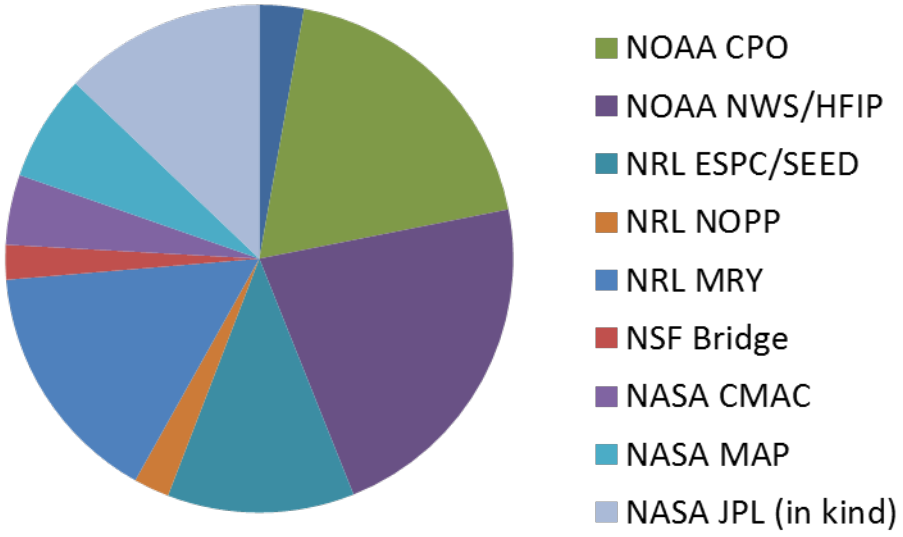
This task would have been impossible without the regridding capability that ESMF has provided … made it possible to access a large class of data from ocean and sea ice models that could not otherwise be handled …this ESMF interface is allowing us to provide users with much more functionality than we could before … the technical support was exemplary and invaluable …

Themes in these statements:

- ESMF grid remapping allows users to work with grids that they could not work with before (e.g. some CMIP5 model grids)
- The tools are fast and reliable.
- Customer support is excellent.

Governance and Partnerships

- Most development tasks come from user emails to ESMF support. Tasks longer than two weeks are prioritized by a Change Review Board.
- ESMF is directed by a multi-agency Executive Board. This body approves the ESMF Strategic Plan and defines the project's organizational structure and processes.
- Programmatic direction comes from an Interagency Working Group of project sponsors.



New Directions

The initial ESMF software fell short of the vision for common infrastructure in several ways:

1. Implementations of ESMF could vary widely and did not guarantee a minimum level of technical interoperability among sites
2. It was difficult to track who was using ESMF and how they were using it
3. There was a significant learning curve for implementing ESMF in a modeling code

New development directions address these gaps.

The National Unified Operational Prediction Capability

1. *Implementations of ESMF could vary widely and did not guarantee a minimum level of technical interoperability among sites*

- The National Unified Operational Prediction Capability (NUOPC) is a consortium of operational weather prediction centers and their research partners
- NUOPC developed the NUOPC Layer software to increase interoperability of ESMF components
- The NUOPC Layer adds to ESMF:
    - A formalism that describes and splits the phases of initialization
    - A formalism for checking and reporting whether component requirements are satisfied during the run sequence
    - Code templates for drivers, models, mediators (couplers) and connectors, and example application showing a variety of model interactions (e.g. explicit, semi-implicit, implicit coupling)
    - Compliance checkers

The Earth System Prediction Suite

2. It was difficult to track who was using ESMF and how they were using it

- The Earth System Prediction Suite (ESPS) is a collection of weather and climate modeling codes that use ESMF with the NUOPC conventions.
- **The ESPS makes clear which codes are available as ESMF components and modeling systems.**

Draft inclusion criteria for ESPS:

https://www.earthsystemcog.org/projects/esps/strawman_criteria

Model Codes in the ESPS

Currently, components in the ESPS can be of the following types:
coupled system, atmosphere, ocean, wave, sea ice

Target codes include:

- The Community Earth System Model (CESM)
- The NOAA Environmental Modeling System (NEMS) and Climate Forecast System version 3 (CFSv3)
- The MOM5 and HYCOM oceans
- The Navy Global Environmental Model (NavGEM)-HYCOM-CICE coupled system
- The Navy Coupled Ocean Atmosphere Mesoscale Prediction System (COAMPS) and COAMPS Tropical Cyclone (COAMPS-TC)
- NASA GEOS-5
- NASA ModelE

ESPS Code Status

LEGEND

Compliant | (Completion date) In progress | Candidate

Coupled Modeling Systems							
	NEMS	CFSv3	COAMPS / COAMPS-TC	NavGEM-HYCOM-CICE	GEOS-5	ModelE	CESM
	2014	2014			2015	2015	2014
Atmospheres							
GFS/GSM							
NMMB							
CAM							2014
FIM	2014						
GEOS-5 FV					2015		
ModelE Atm						2014	
COAMPS Atm							
NavGEM							
NEPTUNE							
WRF							2014
Oceans							
MOM5							
HYCOM							
NCOM							
MPAS-O							
POP							2014
Ice							
CICE	2014	2014			2014	2014	2014
Wave							
WW3	2014		2014		2014		2014
SWAN							

Spanning major climate, weather, and ocean codes, ESPS is the most direct response to calls for common modeling infrastructure yet assembled

Vision vs Reality in ESPS

Some documents (e.g. NRC 2012) call for a **single** infrastructure that would **replace** all existing agency and organizational infrastructures.

This would be difficult to achieve politically and technically.

A more practical approach allows **multiple** modeling infrastructures to be wrapped and linked.

Using this approach, CESM components, GFDL MOM5 code, and other codes keep their native infrastructure while still being able to run with ESMF/NUOPC conventions.

Cupid Development and Training Environment

3. There was a significant learning curve for implementing ESMF in a modeling code

CUPID GOAL: Make ESMF training and development simpler and more appealing

- NASA funded: NOAA CIRES, GA Tech, and NASA GISS/GSFC collaboration
- "Integrated Development Environment" or IDE
- Customized for ESMF applications with NUOPC conventions

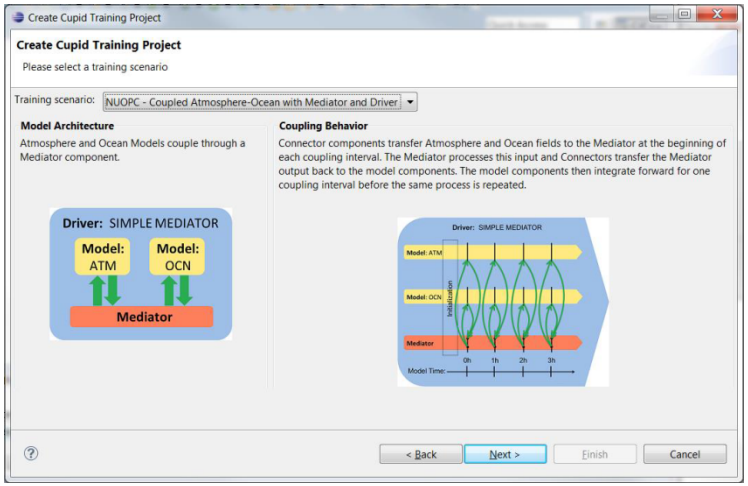
Cupid users see a multi-screen user interface where they can:

- Pick a training problem (or coupled model)
- Generate a trace of the model to see its structure
- Navigate around the model using the trace
- Use an editor to modify the source code
- Automatically generate code needed for NUOPC compliance
- Compile and run locally or on a cloud (currently Amazon Web Services)

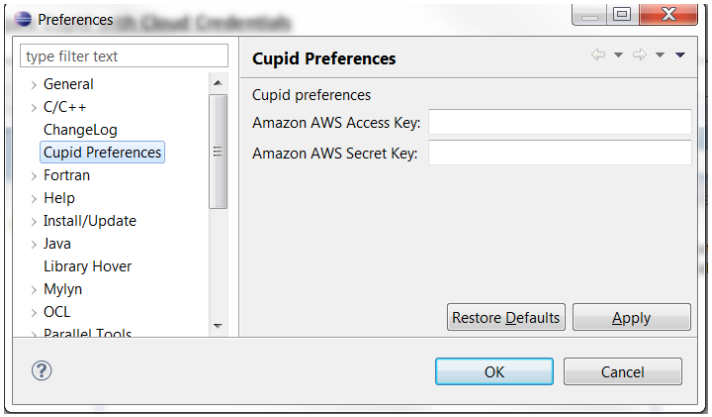
Cupid is a working prototype expected to be ready for first public release in FY14.

Cupid project: https://earthsystemcog.org/projects/cupid/

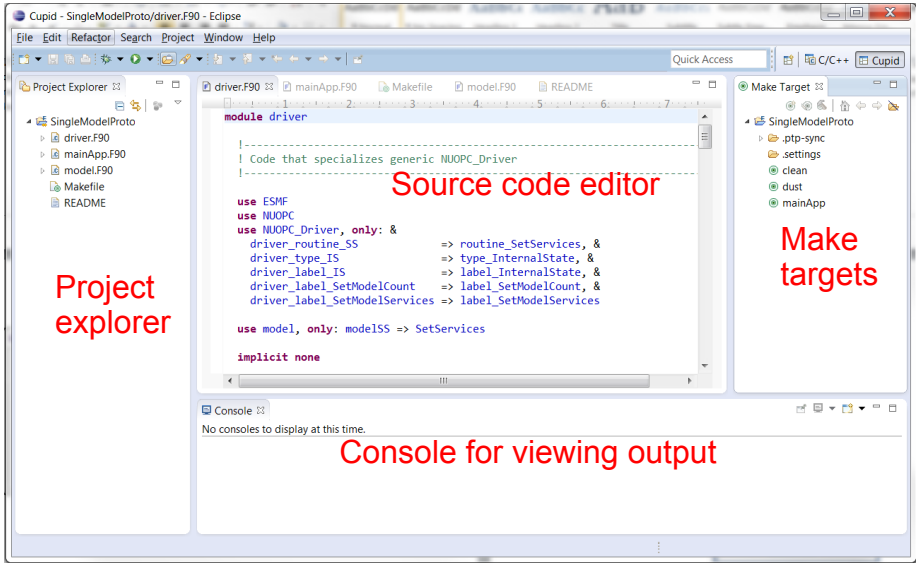
Cupid Development and Training Environment



Select sample code or model



Run locally or on a cloud



- Generate trace of code components/structure
- Navigate code using trace
- Edit source code
- Generate NUOPC code
- Check compliance
- Compile

Coming in 2014 …

ESPS Delivery

•BAMS paper is in progress, target submission June 2014

•Anticipate completion of initial version of coupled NEMS (MOM5 and HYCOM) and CESM-HYCOM before submission

ESMF Development

•Extend ESMF data classes to **recognize accelerators** and extend component classes to **negotiate for resources**
More automated and optimized mapping of multi-component models to hardware platforms

•**Integrate the MOAB finite element mesh library** into ESMF and compare and potentially replace ESMF's original finite element mesh library
Infrastructure development in collaboration with DOE and Navy

•Enable grid remapping to have a **point cloud or observational data stream destination**
Requested by surface modelers for remapping to irregular regions, and by NASA GMAO and other groups engaged in data assimilation

•**Introduce higher order conservative** grid remapping methods
Requested by multiple climate modeling groups

+ First public release of Cupid, new research and outreach lead, outreach plan

In Conclusion: Why is ESMF Different?

What makes ESMF different from center-specific frameworks?

- To satisfy many incoming research and operational requirements, ESMF developers had to design for a wide range of grid, data, time, and component structures – this creates flexibility in the design and supports knowledge transfer
- ESMF infrastructure is built for deployment by modeling and data systems at multiple sites, and well supported (documented, regression tested, responsive support mailing list, examples)
- The infrastructure is resource-effective in that its development is shared among agencies, and its technical path informed by many expert development partners
- Development priorities are set through a clear, formal, multi-agency process
- ESMF spans the often artificial bounds of modeling efforts within agencies, efforts across agencies, and weather and climate time scales